Virtual-photon-induced quantum phase gates for two distant atoms trapped in separate cavities

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We propose a scheme for implementing quantum gates for two atoms trapped in distant cavities connected by an optical fiber. The effective long-distance coupling between the two distributed qubits is achieved without excitation and transportation of photons through the optical fiber. Since the cavity modes and fiber mode are never populated and the atoms undergo no transitions the gate operation is insensitive to the decoherence effect when the thermal photons in the environment are negligible. The scheme opens promising perspectives for networking quantum information processors and implementing distributed and scalable quantum computation.

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In recent years, much attention has been paid to quantum computers, which are based on the superposition principle of quantum mechanics. This type of new machines can solve some problems much more efficient than classical computers. Typical examples are the factorization of a large composite number via Shor's algorithm [1] and the search for an item from a disordered system via Grover's algorithm [2]. It has been shown that the building blocks of quantum computers are two-quantum-bit (qubit) logic gates [3]. Such gates have been demonstrated in cavity QED [4], ion trap [5], and NMR [6] experiments. The cavity QED system with atoms interacting with quantized electromagnetic fields is almost an ideal candidate for implementing quantum information processors because atoms are suitable for storing information and photons suitable for transporting information. A number of robust schemes have been proposed for implementing quantum gates for two atoms trapped in a cavity [7-9].

The implementation of a quantum computational task corresponds to the performance of an unitary transformation on the quantum register, which is composed of multiple qubits [10]. For building a quantum computer that has practical applications a large number of qubits should be ensembled and the power of quantum computers increases as the number of qubits increases. However, there are physical limitations on the number of qubits in a quantum computer and large-scale quantum computation has not been experimentally achieved yet. To overcome this limit, several distinct quantum information processors should be connected via quantum channels to form a powerful quantum computer. Entanglement and controlled-phase gates between two distant atoms have been proposed [11,12]. The schemes are probabilistic and the success probability depends upon the efficiency of photodetectors. Moreover, the success probability decreases as the number of qubits increases.

Schemes have been proposed for quantum communication between two atoms trapped in distant optical cavities connected by an optical fiber [13]. These schemes are based on accurately tailored sequences of pulses or adiabatic passage. Recently, Serafini et al. [14] suggested a scheme for realizing quantum gates between two two-level atoms in distant optical cavities coupled by an optical fiber. The scheme is based on the Rabi oscillation of the whole system composed of the atoms, cavity modes, and fiber mode. Yin and Li generalized the idea to the multi-atom case [15]. In all of the previous schemes for quantum communication the quantum state is mediated by photons carried by the optical fiber and thus the fidelity is significantly affected by the loss of photons. Furthermore, in Refs. [14] and [15] the controlled-phase gates are obtained under the condition that the atom-cavity coupling strength is much smaller than the cavity-fiber coupling, which might require the weak couplings. In the weak coupling regime, the decoherence effect arising from the atomic spontaneous emission and cavity decay would invalid the scheme. It has been shown that a quantum computer can work only when the individual gate infidelity is below a certain constant threshold, which is about 10^{-2} [16]. The implementation of deterministic high-fidelity quantum gates between two qubits at different nodes is a prerequisite for realizing distributed and scalable quantum computation.

In this paper we propose an alternative scheme for controlled-phase gates between two atoms trapped in two distant optical cavities. The distinct feature of our scheme is that the two distant qubits are coupled without exciting and transferring photons through the optical fiber, which is in contrast with the previous quantum networking schemes. The long-range interaction is mediated by the vacumm fields of the cavities and fiber and the whole system evolves in the decoherence-free subspace, in which neither of the subsystems is excited. Thus the scheme is insensitive to the atomic spontaneous emission, cavity decay, and fiber loss when the thermal photons in the environment are negligible. Furthermore, our scheme does not require the atom-cavity coupling to be smaller than the cavity-fiber coupling. These features make the scheme very promising for implementation of distributed

and scalable quantum computation that can avoid decoherence.

We consider that two identical atoms are trapped in distant cavities connected by a single-transverse-mode optical fiber, as shown in Fig. 1. The number of longitudinal modes of the fiber that significantly interact with the corresponding cavity modes is on the order of $l\,\bar{\nu}\,/(2\pi c)$, where l is the length of the fiber and $\bar{\nu}$ is the decay rate of the cavities' fields into the continuum of the fiber modes. In the short fiber limit $l\,\bar{\nu}\,/(2\pi c) \leq 1$, only one fiber mode essentially interacts with the cavity modes [14]. In this case the coupling between the cavity modes and fiber is given by the interaction Hamiltonian

$$H_{c,f} = \nu b(a_1^\dagger + e^{i\varphi}a_2^\dagger) + H.c., \tag{1}$$

where b is the annihilation operator for the fiber mode, $a_j^\dagger$ is the creation operator for the jth cavity mode, ν is the cavity-fiber coupling strength, and φ is the phase due to propagation of the field through the fiber. Each atom has one excited state $|e\rangle$ and two ground states $|g\rangle$ and $|f\rangle$, as shown in Fig. 2. The transition $|e\rangle \longleftrightarrow |g\rangle$ is coupled to the corresponding cavity mode with the coupling constant g and a classical laser field with the Rabi frequency Ω. The detunings of the cavity mode and classical field are Δ and $\Delta-\delta$, respectively. During the interaction, the state $|f\rangle$ is not affected. In the interaction picture, the Hamiltonian describing the atom-field interaction is

$$H_{a,c} = \sum_{j=1}^{2}[(ga_je^{i\Delta t} + \Omega e^{i(\Delta-\delta)t})\,|e_j\rangle\,\langle g_j| + H.c.]. \tag{2}$$

Define $c_0 = \frac{1}{\sqrt{2}}(a_1 - e^{i\varphi}a_2)$, $c_1 = \frac{1}{2}(a_1 + e^{i\varphi}a_2 + \sqrt{2}b)$, and $c_2 = \frac{1}{2}(a_1 + e^{i\varphi}a_2 - \sqrt{2}b)$. Here c_0, c_1, and c_2 are three bosonic modes, which are linearily relative to the field modes of the cavities and fiber. Then we can rewrite the whole Hamiltonian in the interaction picture as

$$H = H_0 + H_i, \tag{3}$$

where

$$H_0 = \sqrt{2}\nu c_1^\dagger c_1 - \sqrt{2}\nu c_2^\dagger c_2, \tag{4}$$

and

$$\begin{aligned} H_i \;=\; & [\frac{1}{2}g(c_1 + c_2 + \sqrt{2}c_0)e^{i\Delta t} + \Omega e^{i(\Delta-\delta)t}]\,|e_1\rangle\,\langle g_1| \\ & +[\frac{1}{2}g(c_1 + c_2 - \sqrt{2}c_0)e^{-i\varphi}e^{i\Delta t} \\ & +\Omega e^{i(\Delta-\delta)t}]\,|e_2\rangle\,\langle g_2| + H.c. \end{aligned} \tag{5}$$

We now perform the unitary transformation e^{iH_0t}, and obtain

$$\begin{aligned} H_i^{'} \;=\; & \{\frac{1}{2}g[e^{i(\Delta-\sqrt{2}\nu)t}c_1 + e^{i(\Delta+\sqrt{2}\nu)t}c_2 + \sqrt{2}e^{i\Delta t}c_0] \\ & +\Omega e^{i(\Delta-\delta)t}\}\,|e_1\rangle\,\langle g_1| + \{\frac{1}{2}ge^{-i\varphi}[e^{i(\Delta-\sqrt{2}\nu)t}c_1 \\ & +e^{i(\Delta+\sqrt{2}\nu)t}c_2 - \sqrt{2}e^{i\Delta t}c_0] + \Omega e^{i(\Delta-\delta)t}\}\,|e_2\rangle\,\langle g_2| \\ & +H.c.. \end{aligned} \tag{6}$$

We here assume that $\Delta \gg \sqrt{2}\nu,\ \delta,\ g,\ \Omega$. Then the atoms do not exchange energy with the cavity modes, fiber mode, and classical fields due to the large detuning. The quantum information is encoded in the two ground states $|g\rangle$ and $|f\rangle$. Since both the atoms are initially populated in the ground states, they can not exchange excitation with each other via the virtual excitation of the cavity modes and they remain in the ground states. However, the three bosonic modes c_0, c_1, and c_2 can be coupled to each other and the classical fields via the virtual excitation of the atoms. So the Hamiltonian $H_i^{'}$ can be replaced by

$$\begin{aligned} H_i^{''} =& -[\lambda_1 e^{i(\delta-\sqrt{2}\nu)t}c_1 + \lambda_2 e^{i(\delta+\sqrt{2}\nu)t}c_2 + \lambda_0 e^{i\delta t}c_0]\,|g_1\rangle\,\langle g_1| \\ & -[\lambda_1 e^{i(\delta-\sqrt{2}\nu)t}c_1 + \lambda_2 e^{i(\delta+\sqrt{2}\nu)t}c_2 - \lambda_0 e^{i\delta t}c_0]e^{-i\varphi}\,|g_2\rangle \\ & \langle g_2| - (\xi_1 e^{-2i\sqrt{2}\nu t}c_1c_2^\dagger + \xi_2 e^{-i\sqrt{2}\nu t}c_1c_0^\dagger \\ & +\xi_0 e^{-i\sqrt{2}\nu t}c_0c_2^\dagger)\,|g_1\rangle\,\langle g_1| - (\xi_1 e^{-2i\sqrt{2}\nu t}c_1c_2^\dagger \\ & -\xi_2 e^{-i\sqrt{2}\nu t}c_1c_0^\dagger - \xi_0 e^{-i\sqrt{2}\nu t}c_0c_2^\dagger)\,|g_2\rangle\,\langle g_2| + H.c. \\ & -(\eta + \varepsilon_1 c_1^\dagger c_1 + \varepsilon_2 c_2^\dagger c_2 + \varepsilon_0 c_0^\dagger c_0)(|g_1\rangle\,\langle g_1| + |g_2\rangle\,\langle g_2|), \end{aligned} \tag{7}$$

where $\lambda_0 = \frac{\sqrt{2}g\Omega}{4}(\frac{1}{\Delta} + \frac{1}{\Delta-\delta})$, $\lambda_1 = \frac{g\Omega}{4}(\frac{1}{\Delta-\sqrt{2}\nu} + \frac{1}{\Delta-\delta})$, $\lambda_2 = \frac{g\Omega}{4}(\frac{1}{\Delta+\sqrt{2}\nu} + \frac{1}{\Delta-\delta})$, $\xi_1 = \frac{g^2}{4}(\frac{1}{\Delta+\sqrt{2}\nu} + \frac{1}{\Delta+\sqrt{2}\nu})$, $\xi_2 = \frac{\sqrt{2}g^2}{4}(\frac{1}{\Delta-\sqrt{2}\nu} + \frac{1}{\Delta})$, $\xi_3 = \frac{\sqrt{2}g^2}{4}(\frac{1}{\Delta+\sqrt{2}\nu} + \frac{1}{\Delta})$, $\eta = \frac{\Omega^2}{\Delta-\delta}$, $\varepsilon_0 = \frac{g^2}{4\Delta}$, $\varepsilon_1 = \frac{g^2}{4(\Delta-\sqrt{2}\nu)}$, and $\varepsilon_1 = \frac{g^2}{4(\Delta+\sqrt{2}\nu)}$. Here λ_j ($j = 0, 1, 2$) is the effective coupling between the bosonic mode c_j and the classical fields, ξ_j is the mode-mode coupling, and η and ε_j describe the Stark shifts induced by the classical fields and the bosonic mode c_j, respectively.

Under the conditions δ, $\sqrt{2}\nu$, $\delta-\sqrt{2}\nu$, $\delta+\sqrt{2}\nu \gg \lambda_0$, λ_1, λ_2, ξ_0, ξ_1, ξ_2, the bosonic modes c_0, c_1, and c_2 and can not exchange energy with each other and with the classical fields. The nonresonant couplings between the bosonic modes and the classical fields lead to energy shifts depending upon the number of atoms in the state $|g\rangle$. Meanwhile, the nonresonant mode-mode couplings cause energy shifts depending upon both the excitation numbers of the modes and the number of atoms in the state $|g\rangle$. The effective Hamiltonian is

$$\begin{aligned} H_e \;=\; & (\mu_1 + \mu_2)(|g_1\rangle\,\langle g_1| + |g_2\rangle\,\langle g_2|)^2 \\ & +\mu_0(|g_1\rangle\,\langle g_1| - |g_2\rangle\,\langle g_2|)^2 + \frac{\xi_1^2}{2\sqrt{2}\nu}(c_1c_1^\dagger - c_2c_2^\dagger) \\ & (|g_1\rangle\,\langle g_1| + |g_2\rangle\,\langle g_2|)^2 + [\frac{\xi_2^2}{\sqrt{2}\nu}(c_1c_1^\dagger - c_0c_0^\dagger) \\ & +\frac{\xi_0^2}{\sqrt{2}\nu}(c_0c_0^\dagger - c_2c_2^\dagger)](|g_1\rangle\,\langle g_1| - |g_2\rangle\,\langle g_2|)^2 \\ & -(\eta + \varepsilon_1 c_1^\dagger c_1 + \varepsilon_2 c_2^\dagger c_2 + \varepsilon_0 c_0^\dagger c_0)(|g_1\rangle\,\langle g_1| + |g_2\rangle\,\langle g_2|), \end{aligned} \tag{8}$$

where $\mu_0 = \frac{\lambda_0^2}{\delta}$, $\mu_1 = \frac{\lambda_1^2}{\delta-\sqrt{2}\nu}$, and $\mu_2 = \frac{\lambda_2^2}{\delta+\sqrt{2}\nu}$. Here μ_j ($j = 0, 1, 2$) is the effective coupling between the atoms

due to the nonresonant coupling between the bosonic mode c_j and the classical fields. The Hamiltonian describes a four-photon process which is induced by the virtual excitation of the atoms and bosonic modes. The quantum numbers of the bosonic modes c_0, c_1, and c_2 conserve during the interaction. Suppose that the two cavity modes and the fiber mode are all initially in the vacuum state (at the optical frequencies, the thermal photons are negligible). Then the three bosonic modes c_0, c_1, and c_2 remain in the vacuum state during the evolution. In this case the effective Hamiltonian reduces to

$$\begin{aligned} H_e &= (\mu_1+\mu_2)(|g_1\rangle\langle g_1|+|g_2\rangle\langle g_2|)^2 \\ &+\mu_0(|g_1\rangle\langle g_1|-|g_2\rangle\langle g_2|)^2 \\ &-\eta(|g_1\rangle\langle g_1|+|g_2\rangle\langle g_2|). \end{aligned} \tag{9}$$

Due to the nonresonant coupling between the classical fields and vacuum bosonic modes induced by the virtual excitation of the atoms, the atomic system undergoes an energy shift, which is nonlinear in the number of the atoms in the ground state $|g\rangle$. The nonlinear energy shift leads to the evolution

$$\begin{aligned} |g_1\rangle|g_2\rangle &\longrightarrow e^{-i(4\mu_1+4\mu_2-2\eta)t}|g_1\rangle|g_2\rangle, \\ |g_1\rangle|f_2\rangle &\longrightarrow e^{-i(\mu_1+\mu_2+\mu_0-\eta)t}|g_1\rangle|f_2\rangle, \\ |f_1\rangle|g_2\rangle &\longrightarrow e^{-i(\mu_1+\mu_2+\mu_0-\eta)t}|f_1\rangle|g_2\rangle, \\ |f_1\rangle|f_2\rangle &\longrightarrow |f_1\rangle|f_2\rangle. \end{aligned} \tag{10}$$

A two-qubit quantum phase gate is obtained after the qubit-qubit coupling and the single-qubit phase shifts: $|g_j\rangle \longrightarrow e^{i(\mu_1+\mu_2+\mu_0-\eta)t}|g_j\rangle$. The atomic system undergoes a conditional phase shift $-2(\mu_1+\mu_2-\mu_0)t$ if and only if the two atoms are initially in the state $|g_1\rangle|g_2\rangle$. The conditional phase shift is adjustable via the interation time. For the implementation of a given quantum computational task, the single-qubit phase shifts might be unnecessary as they can be absorbed into the next single-qubit rotations. During the operation, all the the atoms, cavity modes and fiber mode are not excited and the decoherence is suppressed when the thermal photons in the environment are negligible.

We briefly address the experimental feasibility of the proposed scheme. Set $\Omega = g$, $\Delta = 30g$, $\delta = g$, $\nu = \sqrt{2}g$, and $\Gamma = \kappa = 0.01g$, where Γ and κ are the decay rates for the atomic excited state and the bosonic modes, respectively. In this case the probability that the atoms undergo a transition to the excited state due to the off-resonant interaction with the classical fields is $P_1 \simeq \Omega^2/\Delta^2 \simeq 1.11\times10^{-3}$. Meanwhile, the probability that the three modes c_0, c_1, and c_2 are excited due to nonresonant coupling with the classical modes is $P_2 \simeq \lambda_0^2/\delta^2 + \frac{\lambda_1^2}{(\delta-\sqrt{2}\nu)^2} + \frac{\lambda_2^2}{(\delta+\sqrt{2}\nu)^2} \simeq 0.917\times10^{-3}$. Therefore, the effective Hamiltonian (11) and (13) is valid. During the procedure all the atoms and bosonic modes are only virtually excited. The effective decoherence rates due to the atomic spontaneous emission and the decay of the bosonic modes are $\Gamma' \simeq P_1\Gamma \simeq 1.11\times10^{-5}g$ and $\kappa' \simeq P_2\kappa \simeq 0.917\times10^{-5}g$, respectively. The time needed to produce a conditional phase 0.15π is $t = 101.25\pi/g$. The infidelity induced by the decoherence is about $(\Gamma'+\kappa')t \simeq 0.645\times10^{-2}$, which is below the threshold 0.01 for fault-tolerant computing and error correction. For the same decoherence rates $\Gamma=\kappa=0.01g$, the infidelity of such a gate achieved in the scheme of Ref. [14] is about 0.7×10^{-1}. The infidelity increases with the conditional phase. For $\Gamma=\kappa=0.01g$ the infidelity of the π-phase gate in our scheme is about 4.3×10^{-2}. In contrast, the decoherence completely deteriorates the fidelity of this gate in Ref. [14], which is produced after six Rabi oscillations. It should be noted that the scheme of Ref. [14] requires that the atom-cavity coupling strength be much smaller than the cavity-fiber coupling for the implementation of the controlled-phase gates. In this case it is difficult to achieve strong atom-cavity coupling. In order to estimate the length of the fiber, let us set $\bar{\nu}=1$ GHz [14]. Thus we have $l \leq 1.884$ m. In this case the round-trip time of virtual photons is $t_r \sim 10^{-8}$ s. For $g = 2\pi\times34$ MHz [17], the operation time scale is on the order of 10^{-6}, much longer than t_r. Thus the interaction Hamiltonian holds.

For simplicity, we have assumed that the two atoms have the same coupling with the corresponding cavity modes. Suppose that the two couplings are $g_1 = g$ and $g_2 = rg$, respectively. Then the conditional phase is $-2r(\mu_1+\mu_2-\mu_0)t$. Unlike the scheme of Ref. [14], the conditional phase gate is valid no matter when the two couplings are the same or not. Another advantage of the gate is that the dynamics can be easily controlled. After the gate operation, the interaction can be frozen by switching off the classical fields. In a recent experiment [18], the localization to the Lamb-Dicke limit of the axial motion was demonstrated for a single atom trapped in an optical cavity. The atomic storage time is on the order of 1 s, much longer than the operation time. The near perfect fiber-cavity coupling with the efficiency larger than 99.9% can be realized using fiber-taper coupling to high-Q silica microspheres [19].

In conclusion, we have described a protocol for implementing conditional phase gates for two atoms trapped in separate cavities conneced by an optical fiber. Our scheme does not involve the excitation and transportation of photons. The long-distance qubit-qubit interaction is obtained via virtual excitation of the atoms, cavity modes, and fiber mode.Thus the scheme is insensitive to the atomic spontaneous emission, cavity decay, and fiber loss when the thermal photons in the environment are negligible. It is unnecessary to require that the atom-cavity coupling be smaller than the cavity-fiber coupling. The idea may be straightly extended to generate cluster states for multiple atoms each trapped in an optical cavity, which are the resources for the one-way quantum computation [20]. The scheme opens promising perspectives for the realization of distributed and scalable quantum network.

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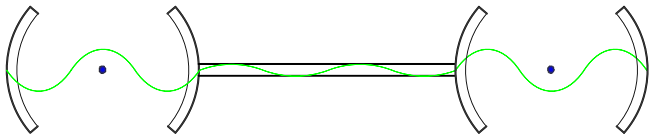

FIG. 1: (Color online) The experimental setup. Two distant atoms are trapped in separate cavities connected by an optical fiber. The two cavity modes are coupled to the fiber mode with the coupling strength ν.

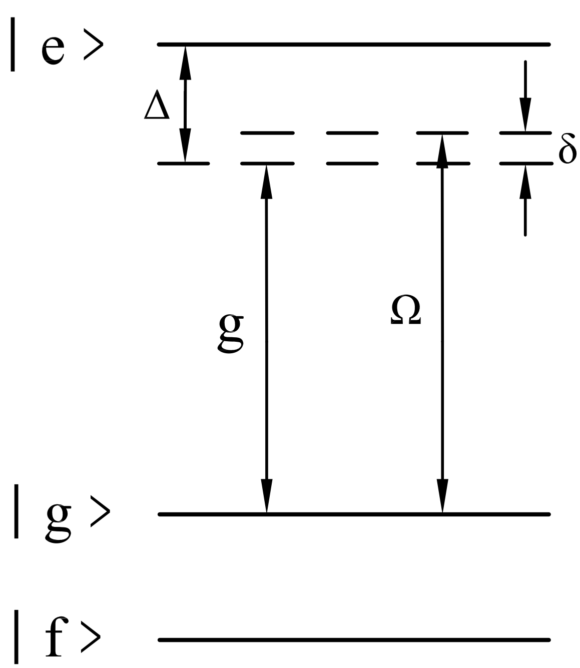

FIG. 2: (Color online) The atomic level configuration. The transition $|e\rangle \longleftrightarrow |g\rangle$ is coupled to the corresponding cavity mode with the coupling constant g and a classical laser field with the Rabi frequency Ω. The detunings of the cavity mode and classical field are Δ and $\Delta - \delta$, respectively.